

**TURBULENCE AND MIXING IN DEEP AND COASTAL OCEANS**

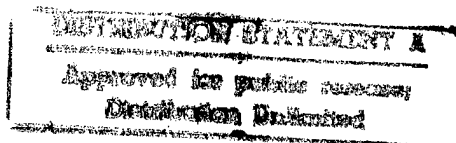
**Final Report of the ONR Contract No.  
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**by**

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13. ABSTRACT (Maximum 200 words) <p>The work completed under this project dealt with two aspects of turbulence and mixing in oceans. The first part of the study was devoted to experimentally investigate the nature of shear-free turbulence near a density interface sandwiched between a turbulent layer and a non-turbulent layer. The experimental results were compared with the predictions of available analytical and numerical models. The entrainment mechanisms and the fate of entrained fluid particles until they homogenize at molecular scales were also studied. These studies were extended to include turbulence on either side of the interface, including the case where there is a turbulent intensity gradient across the interface. Theoretical arguments were developed to predict the mixing rate for the latter case, with which the experimental results were compared. Finally, mean velocity shear was introduced across the interface and the resulting shear instabilities were studied systematically.</p> <p>In the second part of the investigation, an experiment was designed and constructed to study the nature of oscillatory boundary layers, with applications to the oceanic bottom wave boundary layer. Experiments with laminar boundary layers were completed, and studies on the turbulent case were initiated.</p>				
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## 1. Introduction:

During the contract period, the principal investigator H.J.S. Fernando, graduate students Rajka Krstic and Eric Strang, post-doctoral fellow Andrew Folkard, and visiting scientists Professors Eliezer Kit (Tel Aviv University) and J.C.R. Hunt (U.K. Meteorological Office) worked on several problems related to turbulent mixing in stably stratified fluids. In addition, they initiated an experimental program on the coastal-ocean bottom boundary layer. The results of the completed studies are outlined below. The experiments on the bottom boundary layer are still in progress as a part of a continuation grant. Relevant publications originated from the P.I.'s group during the contract period are listed at the end of this report.

### Measurement of Turbulence Near Shear-Free Density Interfaces

An experimental study was carried out to investigate the structure of turbulence near a shear-free density interface. The experimental configuration consisted of a two-layer fluid medium in which the lower layer was maintained in a turbulent state by an oscillating grid. The measurements included the root-mean-square (r.m.s.) turbulent velocities, wave-number spectra, dissipation of turbulent kinetic energy and integral lengthscales. It was found that the introduction of a density interface to a turbulent flow can strongly distort the structure of turbulence near the interface wherein the horizontal velocity components are amplified and the vertical component is damped. The modification of r.m.s velocities is essentially limited to distances smaller than about an integral lengthscale. Inspection of spectra shows that these distortions are felt only at small wave numbers of the order of integral scale and a range of low-wave numbers of the inertial sub-range; the distortions are pronounced as the interface is approached. Comparison of the horizontal velocity data with the Rapid Distortion Theory (RDT) analyses of Hunt and Graham (J. Fluid Mech., **84**, 209-235, 1978) and Hunt (J. Fluid Mech., **138**, 161-184, 1984) showed a qualitative agreement near the interface and a quantitative agreement away from the interface. The RDT predictions for the vertical component, however, were in general agreement with the data. The near-interface horizontal velocity data, however, showed a quantitative agreement with a model

proposed by Hunt (1984) based on non-linear vortex dynamics near the interface. The effects due to interfacial waves appear to be important for distances less than about 10% of the integral lengthscale. As a result of the non-zero energy flux divergence, the introduction of a density interface to oscillating grid turbulence increases the rate of dissipation in the turbulent layer except near the interface where a sharp drop occurs. These measurements provide useful information on the structure of turbulence in shear-free boundary layers, such as atmospheric and oceanic convective boundary layers, thus improving modeling capabilities of such flows.

### **Frequency Spectra in Zero-Mean-Shear Turbulence**

Eulerian frequency spectra were measured in zero-mean-shear (oscillating-grid induced) turbulent flows and were compared with the spectral form proposed by Tennekes (J. Fluid Mech., 67, 561, 1975). The aim was to verify some of the available models for the four-dimensional space-time spectrum of homogeneous turbulence. This spectrum is of immense utility for the Rapid Distortion Theory calculations of turbulence near density interfaces. A good agreement between the theoretical prediction and experimental results were obtained in a limited frequency range. The empirical constants pertinent to the spectral law, obtained experimentally, were in good agreement with numerical simulation results.

### **Evolution of Kelvin-Helmholtz Billows**

A mixing mechanism prevalent in natural flows is the formation and breakdown of vortical billows known as Kelvin-Helmholtz (K-H) instabilities. Laboratory experiments were carried out to study certain key features of K-H billows, wherein the billows were generated in a two-layer stratified tilt-tank. It was shown that small-scale turbulent mixing is present within billows from the early stages of their evolution, but mixing becomes intense and the billows are destroyed as they achieve a maximum height and initiate collapse at a non-dimensional time of  $\Delta U t / \lambda \approx 5$ , where  $\Delta U$  is the velocity shear and  $\lambda$  is the wavelength. When  $\Delta U t / \lambda < 5$ , the Thorpe scale  $L_T$  and the maximum Thorpe displacement  $(L_T)_{\max}$ , normalized by the local billow height  $L_b$ , are independent of both the horizontal location within the billow and time with  $L_T/L_b \approx (0.49 \pm 0.03)$

and  $(L_T)_{\max}/L_b \approx (0.89 \pm 0.02)$ . After the collapse starts, however, the pertinent lengthscale ratios in the “core” of the billow show values similar to those of fully-developed turbulent patches, i.e.,  $L_T/L_b \approx (0.29 \pm 0.04)$  and  $(L_T)_{\max}/L_b \approx (0.68 \pm 0.04)$ . The field observations were found to be in good agreement with laboratory-based predictions.

### **Resuspension of a Particle Bed by a Round Vertical Jet**

An experimental study was carried out to investigate the resuspension (fluidization) of a loosely held monodispersed particle bed by a momentum jet discharging from below. The work was motivated by its applications to limnological situations where the bottom sediments are suspended by a series of jets fed by a groundwater karstic system. Two different flow regimes were identified, and the conditions under which they occur were mapped on a regime diagram between the two important non-dimensional variables,  $h_o/d_p$  and  $h_o(M_o^{1/2}/w_s)$ , where  $h_o$  is the height of the particle layer,  $w_s$  is the particle-settling velocity and  $M_o$  is the momentum flux of the jet. The maximum height of rise of particles within the jet was also determined as a function of these non-dimensional variables. Comparisons of laboratory and field observational results were also made.

### **Turbulent Wakes of Stratified Flow Past a Cylinder**

Laboratory measurements were carried out to investigate the evolution of a turbulent wake behind a right circular cylinder moving in a linearly stratified fluid. The flow field is determined by the internal Froude number  $Fi$  and the Reynolds number  $Re$ , but at high  $Re$ ,  $Fi$  becomes the only governing parameter. Measurements show that stratified turbulent wakes can be classified into three flow regimes, based on  $Fi$ . When  $Fi \lesssim 2$ , the wakes do not grow downstream, and remain at approximately constant height. For  $2 \lesssim Fi \lesssim 3$ , the wakes grow to a maximum height at  $Nt \approx 5$  and then collapse physically; for  $Nt \gtrsim 3$ , the maximum height is achieved at  $Nt \approx 2.5$ , before the collapse begins. The evolution of such other length scales as the Ozmidov, Kolmogorov, overturning and Thorpe scales and the maximum Thorpe displacements were measured, and their behavior in the above  $Fi$  ranges delineated. Length scale diagrams for the evolution of stratified

turbulence in cylinder wakes were constructed, and were compared with previous theoretical predictions. These results provided new insights into the evolution, collapse and two-dimensionalization of stratified turbulent flows.

### **Migration of Density Interfaces Subjected to Differential Turbulent Forcing**

A laboratory study was performed on the migration of sharp density interfaces in the presence of differential turbulence levels across them. It was shown that, in a certain parameter range, the net migration rate of the interface can be parameterized (to the first order) as the resultant of the entrainment rates based on either one or the other layer is non-turbulent (i.e., stirring is from one side only). The interface initially migrates in a preferential direction determined by the r.m.s. velocities and the integral lengthscales of turbulence near the interface, and then achieves a quasi-stationary state wherein the system runs down to a homogeneous state due to the buoyancy transport through the interface.

### **List of Publications**

#### **Journal Papers**

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- Chen, R-r., Berman, N.S., Boyer, D.L. and Fernando, H.J.S., "Physical Model of Diurnal Heating in the Vicinity of a Long Mountain," *Journal of the Atmospheric Sciences*, **53(1)**, 62-85, 1996.

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- Kit, E. and Fernando, H.J.S., "Frequency Spectra of Scalar Fluctuations at Entraining Stratified Interfaces," *Fluid Dynamics Research*, **19**, 65-75, 1997.
- Kit, E., Strang, E. and Fernando, H.J.S., "Measurement of Turbulence Near Shear-Free Density Interfaces," *Journal of Fluid Mechanics*, **334**, 293-314, 1997.
- Voropayev, S.A., Zhang, X., Boyer, D.L., Fernando, H.J.S. and Wu, A., "Horizontal Jets in Rotating Stratified Fluids," *Physics of Fluids*, **9**(1), 115-126, 1997.
- Folkard, A., Davies, P.A. and Fernando, H.J.S., "Measurements of Turbulent Patch in a Rotating Linearly Stratified Fluid," *Dynamics of Atmospheres and Oceans* (accepted for publication).
- Xu, Y., Boyer, D.L., Fernando, H.J.S. and Zhang, X., "Motion Fields Generated by the Oscillatory Motion of a Circular Cylinder in a Linearly Stratified Fluid," *Experimental Thermal and Fluid Science* (accepted for publication).

### **Papers Submitted**

- De Silva, I.P.D. and Fernando, H.J.S., "The Collapse of a Turbulent Mixed Region in a Stratified Fluid," *Journal of Fluid Mechanics* (under revision).
- Manasseh, R., Ching, C.Y. and Fernando, H.J.S. "The Transition from Wave-Dominated to Density Driven Isolated Flows," *Journal of Fluid Mechanics* (under revision).
- Neves, J. and Fernando, H.J.S., "Behavior of a Sediment-Laden Vertical Turbulent Jet," *Journal of Fluid Mechanics* (under revision).

Fernando, H.J.S. and Hunt, J.C.R., "Turbulent Mixing Across Shear-Free Density Interfaces; Part 1 - Modeling Considerations," *Journal of Fluid Mechanics* (under revision)

Fernando, H.J.S., McGrath, J. and Hunt, J.C.R., "Turbulent Mixing Across Shear-Free Density Interfaces; Part 2 - Laboratory Experiments," *Journal of Fluid Mechanics* (under revision)

Zhang, X., Boyer, D.L. and Fernando, H.J.S., "Turbulence-Induced Rectified Flows in Rotating Fluids," *Journal of Fluid Mechanics* (under revision)

Fernando, H.J.S., Fonseka, S.V. and van Heijst, G.J.F., "The Evolution of an Isolated Turbulent Region in a Stratified Fluid," submitted for publication.

Lozovatsky, I. and Fernando, H.J.S., "Observations of Turbulence in Marine Stratified Layers," submitted for publication

Fernando, H.J.S. and Buhler, J., "The Scales of Sediment Fingers," submitted for publication

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